REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave Blank)*	2. REPORT DATE January 28, 2011	3. REPORT TYPE AND DATES COVERED Final Technical, 01/01/08 – 11/30/10

4. TITLE AND SUBTITLE
Minimizing Surface Plasmas in High Power Microwave Sources

5. FUNDING NUMBERS
FA9550-08-1-0068

6. AUTHORS
Edl Schamiloglu, Christopher Watts, and Mark Gilmore

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of New Mexico
MSC01 1100
Department of Electrical and Computer Engineering
Albuquerque, NM 87131-1356

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/RSE
875 North Randolph Street, Suite 325
Arlington, VA 22203-1768

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

AFRL-OSR-VA-TR-2012-0214

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Unlimited

12b. DISTRIBUTION CODE
AFOSR/RSE

13. ABSTRACT *(Maximum 200 words)*
This final technical report reviews the research activities during the period of this grant, emphasizing the final year. The effects of surface roughness on secondary electron emission were investigated for copper. The surface of copper samples were modified using a high-power Nd-YAG laser, where the degree of surface modification depended on the duration and intensity of the laser exposure. Four different levels of modification were tested, in addition to the unmodified sample. Minor modification resulted in the biggest effect, significantly reducing the secondary electron emission. However, this effect only holds true for very low electron dose, where dose is the incident charge per unit area. For higher dose levels – those commensurate with "technical materials" in applied situations – there was negligible effect of surface roughness on secondary electron emission. The data set presented here seeks to quantify the effect of surface roughness with further gradations than is accounted for in the semi-empirical formulae in the literature.

14. SUBJECT TERMS
secondary electron emission, laser-material interaction, dose effect, high power microwaves, depressed collector.

15. NUMBER OF PAGES
18

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	None

THE UNIVERSITY of NEW MEXICO SCHOOL of ENGINEERING

Department of Electrical & Computer Engineering

"Minimizing Surface Plasmas in High Power Microwave Sources"

Final Technical Report
1 January 2008 – 30 November 2010

28 January 2011

Submitted by:

Edl Schamiloglu — Principal Investigator and Professor
Department of Electrical and Computer Engineering
University of New Mexico
Albuquerque, NM 87131
Tel. (505) 277-4423
Fax: (505) 277-1439
e-mail: edl@ece.unm.edu

and:

Mark Gilmore – Associate Professor
Department of Electrical and Computer Engineering
University of New Mexico
Albuquerque, NM 87131
Tel. (505) 277-2579
Fax: (505) 277-1439
e-mail: gilmore@ece.unm.edu

Christopher Watts – Research Professor
Department of Electrical and Computer Engineering
University of New Mexico
Albuquerque, NM 87131
Tel. (505) 277-2436
Fax: (505) 277-1439
e-mail: cwatts@ece.unm.edu

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I. INTRODUCTION

Secondary electron emission (SEE) is the liberation of electrons from a material due to bombardment by a beam of charged particles. Like any physical phenomenon, there are practical applications where a large secondary emission is desirable (as in photomultiplier tubes) and situations when a large secondary emission may be problematic (*e.g.* accelerator rings) [1,2]. A generalized theory of secondary electron emission from all materials (metals, semiconductors, dielectrics, *etc.*) poses an overwhelmingly complicated problem. Even when limiting the discussion to only metals, unsatisfactory agreement is observed between proposed classical and quantum mechanical theories and many published experimental results (see, for example, references in [1]). However, such disagreement may be attributed to missing experimental details, in particular the surface properties of the substrate under investigation.

One undesirable manifestation of SEE is in depressed collectors of high power microwave (HPM) sources. HPM devices, such as gyrotrons and gyroklystrons, may suffer deleterious effects due to secondary electrons produced from surfaces exposed to the spent electron beam. Reducing secondary electron emission from collectors can significantly increase efficiency in such cases. Our primary motivation is to investigate possible methods of reducing secondary electron emission, which could potentially be of benefit for collectors of HPM devices. As such, in these studies we are interested in the secondary emission from "technical materials," *i.e.* materials that may not necessarily be pure and are used *in situ*, where the measured secondary emission may not coincide with the number of "true" secondary electrons [3]. ("True" secondary electrons are those actually emitted from the material, as opposed to backscattered beam electrons.)

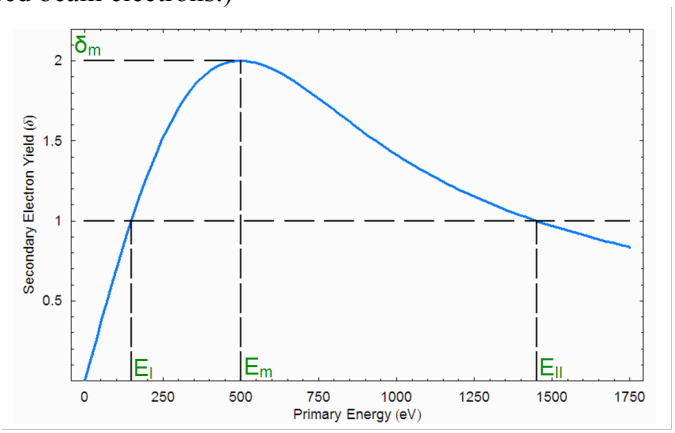

Figure 1. Generic secondary electron emission curve showing the SEY as a function of electron beam energy.

An important parameter used to measure the secondary emission of a substance is the secondary electron yield (SEY), defined as the ratio of liberated or secondary electrons to incident or primary electrons, and is commonly denoted by δ. The secondary electron yield is defined by

$$\delta = \frac{I_s}{I_p} \tag{1}$$

where I_p is the incident or primary electron beam current and I_s is the secondary emission current liberated from the sample. A generic SEY curve is shown in Fig. 1. δm is the maximum yield, and Em is the energy at maximum yield. EI and EII represent crossover energies, *i.e.,* points at which the

secondary yield is unity. The existence of a universal reduced-yield curve (δ/δm versus E /Em) in the case of metals (this paper limits discussion to secondary emission from metals) was first proposed by Baroody [4]. Equations relating δ/δm to E/Em have been proposed by Lye and Dekker [5], Dionne [6,7], and Vaughan [8,9]. Because the secondary emission process is very complicated, these models tend to be largely empirical, though Dionne includes some physical interpretation of the parameters. As such, the roles surface chemistry, surface roughness, electrical conductivity, *etc.,* play is generally not explicit.

In earlier research under the auspices of this AFOSR grant we showed that the act of measuring SEE itself can lead to a decrease in secondary emission [1]. This is termed the "dose effect," and, though known, has been poorly studied and documented [1-3]. The effect is manifest through a decreasing secondary electron yield with exposure time to the probing electron beam. Increased beam current leads to stronger SEE reduction, and hence time-integrated electron current or "electron dose" (total coulombs incident on the sample) appears to be the relevant parameter. In the limited number of papers addressing this issue, it is agreed that the dose effect is likely a consequence of the formation of carbon deposits during electron bombardment; XPS analysis of the samples after exposure confirms the enhanced carbon buildup in the area of interaction [1]. The origin of the carbon is uncertain, but we postulate that it is likely from the stainless steel walls of the measurement vacuum chamber [1].

From these studies, we were curious whether the chemical composition (*i.e.* carbon) of the deposit was primarily responsible for the decreased yield, or if possibly the amorphous, rough nature of the deposit played the dominant role. Hence, we undertook a series of studies to test the role of surface roughness on secondary emission. We systematically modified the surface roughness using a high power laser and compared the resulting secondary emission.

II. SURFACE MODIFICATION

The objective of the main set of experiments performed during the third year of this grant was to test to what extent the properties of the substrate surface affect secondary electron emission. It seems plausible that with a rougher surface the secondary emission should decrease, since, at the atomic level, the uneven surface presents enhanced opportunity for electron recapture. On the other hand, the increased surface area may lead to increased secondary emission, since the distance to the surface is on average shorter for any liberated electron.

We emphasize again, that we are interested in the secondary emission of technical materials. For the typical application of such materials, a large incident electron current indicates that the dose effect will be important. To disentangle the dose effect from the effects of surface roughness on secondary yield, we undertook a series of experiments with time resolved measurements. The sample was first roughened to varying degrees using a laser as described below. Then the SEY was measured at progressively increasing dose. As demonstrated in previous work [1-3], at the lowest dose there is essentially no carbon deposited on the sample, while increasing dose (*i.e.* increased time of exposure to the electron beam) results in a substantial deposition of carbon and a consequent reduction in secondary electron yield. If the roughened samples show a marked decrease in SEY even at low dose, this would imply that surface roughness – and by implication the rough nature of the amorphous carbon deposited with the dose effect, rather than carbon chemistry – is the likely factor reducing SEY.

We chose to use a copper substrate for these tests; copper has been extensively studied, and its secondary yield curve has been well documented. The sample used is commercial-grade (*i.e.* nominally "pure" copper, but likely containing a small impurity component) 1 mm-thick copper sheeting. The surface was prepared by first buffing with fine (#00 grade) copper wool until a near mirror-like sheen was obtained; though highly reflective, small random abrasions and scratches were still visible. The surface was subsequently cleaned with an acetone wipe and then with a methanol wipe. It was immediately inserted into the vacuum chamber and pumped down to vacuum ($\sim 7 \times 10^{-8}$ Torr).

The substrate surface was then modified with laser ablation. We chose this method over more conventional methods, say abrasion with polish, in order to avoid surface contamination with grit. Further, the ablation was performed *in situ* under vacuum to both minimize any chemical reactions during the ablation process, and reduce surface contaminate formation prior to SEE measurement. We used an Nd-YAG (neodymium yttrium-aluminum-garnet) pulsed laser ($\lambda = 1064$ nm) with a 3.5 ns pulse width with up to 200 Hz repetition rate and energy up to 500 mJ/pulse. The laser was focused onto the sample using the optical path depicted in Fig. 2. The laser is first incident on the primary mirror that reflects the Nd-YAG light, but is transparent to the HeNe alignment laser. The beam then passes through a beam expander, which increases the beam diameter by a factor of two, and reduces the power density on subsequent optical components. A periscope assembly with a 1 m focal length lens between the two mirrors is used to focus the beam onto the sample. At the sample the beam spot size is approximately 3 mm in diameter. A photograph of the experimental set-up is also shown in Fig. 2.

In preparing for these experiments we ran several tests to calibrate the effect of the laser interaction at various powers on the reverse side of the sample. The sample was then removed and inspected under magnification. From these tests, we selected four protocols that yielded increasing levels of surface

irregularity. The sample was then re-cleaned and reinserted into the vacuum chamber. Our calibration of "roughness" was visual inspection under magnification. No quantitative measure of roughness was made (*i.e.* profile measurements of vertical deviation amplitude, frequency, *etc.*), as we had no such capability at hand. However, the goal of this work is to determine whether (carbon) chemistry or surface roughness *per se* is principally responsible for reducing SEY in the dose effect; future work might characterize quantitatively surface roughness vs. secondary yield.

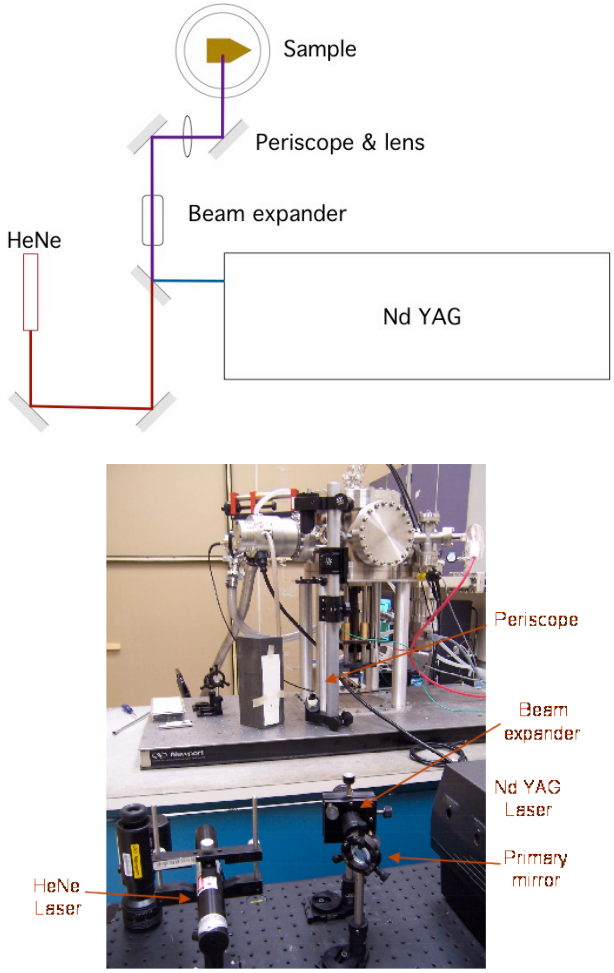

Figure 2. Top: Schematic of the optical beam path from laser to sample. Bottom: Photograph of experimental setup.

The characteristics of the four levels of increasingly severe surface modification, along with the unmodified surface, are summarized in Table 1. The least severe case we refer to as *topical cleaning*. For this case there is almost no visible change to the sample; the nomenclature refers to the observation that, at this level of laser interaction, visible carbon deposits on uncleaned samples are removed. *Minor* modification removed the sheen from the polished sample surface, leaving a dull spot. With *strong* modification there was some evidence of increased surface roughness to the naked eye. With *severe* modification there appeared to be evidence of pitting. Two spots were made at each modification level; one spot for the SEE measurement, and the second spot for *post facto* surface roughness measurements. This was done in case the SEE measurements somehow further modified the surface morphology. No difference between the two sets, however, was observed.

Table 1. Summary of surface modification parameters.

Taxonomy	Modification Characteristics	Laser Power	Duration (at 60 Hz)
Unmodified	As prepared sample with no laser ablation	–	–
Topical Cleaning	No visible damage to sample.	50 mJ	1 min
Minor	Dull spot appears on sample where sheen is removed.	150 mJ	1 min
Strong	Dull spot in conjunction with increased surface roughness	150 mJ	5 min
Severe	Dull spot and evidence of surface pitting	150 mJ; 250 mJ	20 min; 10 min

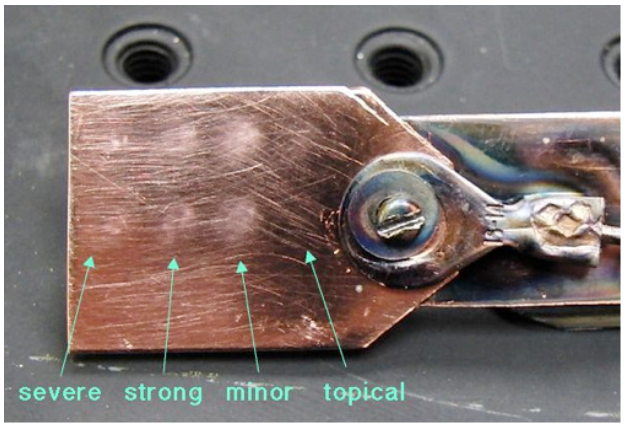

Figure 3. Photograph of a sample's surface showing the location of the modifications.

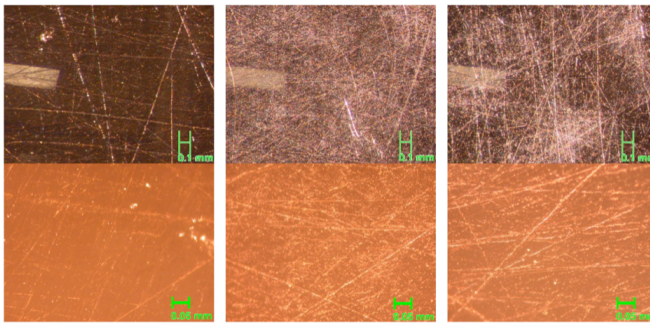

Figure 4. Magnified images showing details of the unmodified, and the *minor* and *severe* modification regions. Note the uniform stippling of the *minor* region, versus the blotchiness of the *severe* region. The bottom row shows the same samples with higher magnification. The *minor* region shows the most uniform surface roughness. The bright band on the left side of the photograph is an artifact. The hash marks indicate 0.1 and 0.05 mm.

The sample with the laser-modified regions is shown in Fig. 3 and photographs of individual regions under 6x and 20x magnification are in Fig. 4; these are photographs of the regions impacted by the electron beam, and were taken *after* the SEE measurements described below. Under the microscope (6x) the unmodified sample was largely smooth (save for the abrasions and scratches), while the *minor* region showed a uniformly rough pattern, somewhat like how fine-grained sandpaper appears to the naked eye. (The *topical* case also showed some evidence of a slight graininess compared with the unmodified case.) Both the *strong* and *severe* cases appeared blotchy, with regions of increased surface roughness interspersed with smoother regions. The pitting as seen by the naked eye was not apparent under the microscope, and is likely an artifact of the non-uniform surface modification. At higher magnification (20x) the *severe* region appeared, on average, to be much less rough than the *minor* region. The reason for this (counterintuitive) difference in laser interaction effect is the subject of speculation. Possibly at higher energies the laser spot itself is less uniform. Or, since at the low laser energies the shot-to-shot power variation is large, the laser randomly and more uniformly modifies the interaction region. In any case, results are qualitatively reproducible, since both spots with the same modification level appeared similar.

The typical electron beam diameter used to measure the secondary emission is about 1 mm for these studies, or 1/3 the diameter of the laser interaction region. After the SEE measurements the region of beam interaction with the sample was not apparent, even under the microscope. Previous work [1] had seen visible evidence of the beam-substrate interaction, which through XPS measurements, was determined to be carbon deposits. Possibly, the lower dose combined with the polishing with copper wool (not done previously) made carbon deposit formation less obvious.

III. SUMMARY OF SECONDARY ELECTRON EMISSION RESULTS

The SEE was measured using the automated system as described in [1]. Essentially, an electron gun creates a focused electron beam incident on the sample under study. The current through the sample is measured with a sensitive ammeter. The system measures the SEY by comparing the current drawn with a grounded sample (yielding the complement to the secondary emission, or target current I_t) to the current with the sample biased strongly positive with respect to ground (yielding the primary or beam current I_p). Then for this case, the SEY can be calculated from

$$\delta = \frac{I_s}{I_p} = 1 - \frac{I_t}{I_p}, \tag{2}$$

where I_s is the secondary emission current liberated from the sample, as in (1).

For these measurements, the system was modified to make multiple scans in energy at very low electron gun emission current to track the effects of increasing dose on secondary yield. The average emission current of the beam was 770 nA, and a total of 25 scans in energy at each modification regions were performed. Using the measured beam area of 0.64 mm^2, the "average" dose incident on the sample during each energy scan was about 130 μC/mm^2, where "average" is the integrated beam current over one energy scan time divided by two. This translates to a total dose of about 275 μC/mm^2 per complete energy scan, which is at the upper end of the range of dose that was studied by Baglin *et al.* [3]. In their work doses in the range of 1 nC/mm^2 to 10 mC/mm^2 were studied, with reduction in SEY significant above about 100 μC/mm^2. On the other hand, this total dose is a factor 25 less than the smallest dose reported in Kumar *et al.* [1]. Thus, the initial energy scan is in the range where the dose effect first manifests itself, and carbon deposits first begin to form.

We first confirm the dose effect. Plotted in Fig. 5 is the secondary electron yield (SEY) of Eq. (1) versus beam energy for the unmodified sample. Shown are energy scans 1, 3, 5, 10, 15, and 25. As expected, there is a clear drop in SEY with increasing dose, which has been previously attributed to carbon deposit buildup in the electron beam impact region [1,2]. Note from above that, under the microscope, there was no obvious carbon deposit formation apparent. However, though XPS surface analysis was not performed on this particular sample, we know from previous work that even at low dose there is significant carbon deposit formation [1].

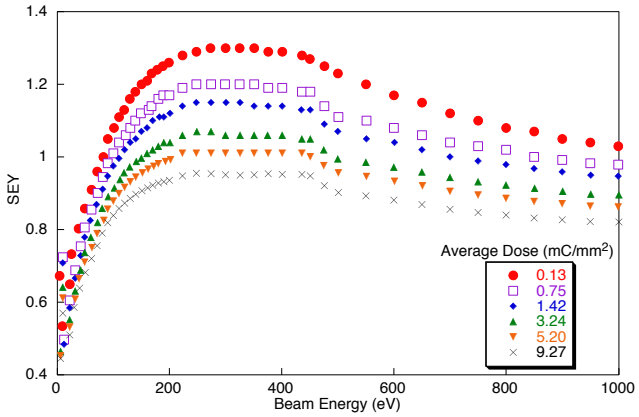

Figure 5. Secondary electron yield as a function of energy for the bare copper (unmodified) sample. The decrease in SEY with increasing dose is prominent.

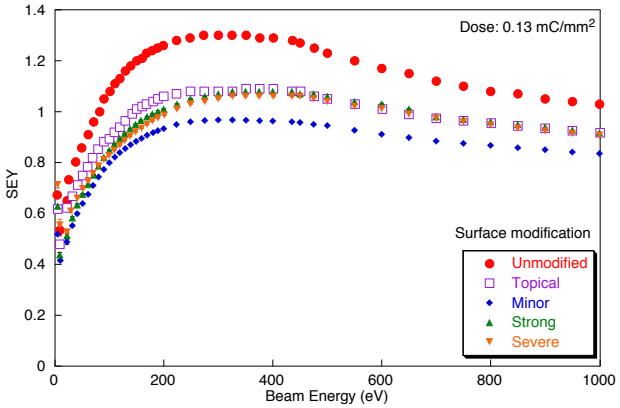

Figure 6. Secondary electron yield as a function of energy for the different surface modifications in the low dose case.

Next, we investigate the effect of surface roughness on the secondary yield at very low dose, where the dose effect is minimal and there is negligible carbon buildup. As seen in Fig. 6, the effects of laser surface modification are quite pronounced at very low dose, *i.e.* for the first energy scan. All cases of surface modification, including the *topical* cleaning case, which showed no apparent change to the surface, show large decrease in SEY over the unmodified case. Paradoxically, the *minor* modification case showed the strongest SEY reduction, while more intense modifications resulted in more modest reductions. We speculate that this is a consequence of the actual modification of the surface by the laser (as opposed to simply laser interaction time/level). For the *minor* modification case a more uniform rough surface was obtained (see Fig. 4). More severe modifications resulted in uneven, patchy surfaces with highly reflective regions. Since the electron beam diameter is large compared to this structure size, it samples both roughened areas and the smoother regions. It appears that the more polished the surface, the greater the secondary yield, and that increased surface roughness can indeed lead to reduce secondary yield, *assuming conditions of low beam dose*.

Results for higher doses (the 25th scan, ~9 mC/mm^2) incident on the modified regions are quite different, as plotted in Fig. 7. The differentiation in SEY for the differing surface conditions all but disappears. All surface modifications show a reduction in SEY to very low levels, though the minor modification case remains slightly lower. Our conclusion is that while increasing the surface roughness can substantially decrease secondary electron emission at low dose, for technical situations where the dose is typically quite large (*i.e.* accelerator rings or microwave tubes) surface roughness, *per se*, will not produce any reduction in SEY beyond normal "conditioning". Further, the results of these studies would indicate that it is the rough, amorphous nature of the carbon deposits, rather than its chemical properties, which plays the essential role in depressing the secondary emission. A uniformly roughened surface evinces suppressed secondary emission even at low dose, while higher doses, with the associated carbon deposits, does not significantly reduce the SEY further.

For comparison we consider the work of Curren and Jensen [10] where secondary electron emission from copper that was textured using an ion beam was investigated. Their motivation for this research was to improve the efficiency of multistage depressed collectors for microwave amplifier traveling-wave tubes for space communications. Their hypothesis was that a textured (roughened) surface would have a lower secondary yield compared with a smooth surface. They observed that, whereas the secondary yield from untreated copper samples were between 0.8 and 1.5 for a variety of angles of incidence, the ion-textured copper samples' secondary yield were between 0.3 and 0.8 over the same range of angles of incidence. However, data for angle of incidence 60° and greater (where 0° represented normal incidence and 90° represented grazing incidence) suggested that the untextured

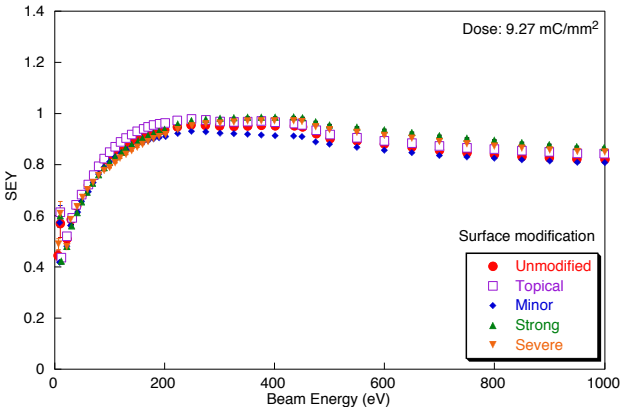

Figure 7. Secondary electron yield as a function of energy for the different surface modifications in the high dose case.

surface performed better than the textured surface (lower secondary electron yield). The incident primary beam energies varied from 200-2000 eV. Unfortunately, there was insufficient information in [10] to determine what the electron dose was.

The data shown in Figs. 6 and 7 also suggest that the roughened surface in the low dose case results in a reduced secondary electron yield. However, the dose effect (as described in detail in [1]) seems to be a more important factor in determining the secondary yield from technical materials for application to high power microwave depressed collectors.

Finally, the data presented in Figs. 6 and 7 is consistent with the data of Bojko, Hilleret, and Scheuerlein for sputter-cleaned copper [11].

IV. CONCLUSIONS

The surface properties of the material under study play a major role in its secondary electron emission characteristics. From these studies, it is clear that surface roughness can significantly impact the secondary electron emission. However, this reduction is all but overwhelmed by the dose effect. Thus, for technical materials, intense electron bombardment may play more of a role in SEY reduction. However, the dose effect appears to be connected with carbon buildup, whose origin is uncertain. To this end, our results would support the hypothesis that it is the amorphous, rough nature of the carbon deposit that is responsible for reducing secondary yield, as opposed to, say, its chemistry. Any carbon deposits in the minor [italics] modification case resulted in only a minimal reduction in SEY beyond that already achieved with the enhanced surface roughness. That said, in a carbon-free environment (*e.g.* pure materials, no stainless steel, *etc.*), perhaps surface roughness can lead to a reduction in secondary emission. It is clear that the data presented here suggest that additional refinement of semi-empirical secondary electron yield formulae in the literature is necessary, accounting for a more fine gradation of surface roughness. Future work should investigate using a more quantitative means for determining surface roughness following laser ablation.

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IX. PERSONNEL, PUBLICATIONS, INTERACTIONS, AWARDS

PERSONNEL

Dr. Edl Schamiloglu	Professor and PI
Dr. Mark Gilmore	Associate Professor and Co-PI
Dr. Christopher Watts	Research Professor
Mr. Christopher J. Leach	Ph.D. Student
Mr. Prashanth Kumar	M.S./Ph.D. Student

PUBLICATIONS

A. Journal Papers

1. G. Zhao, R.P. Joshi, S. Rogers, E. Schamiloglu, and H.P. Hjalmarson, "Simulation Studies for Nonlinear-Transmission-Line-Based Ultrafast Rise Times and Waveform Shaping for Pulsed-Power Applications," *IEEE Trans. Plasma Sci.,* vol. 36, 2618 2625 (2008).

2. M.I. Fuks, E.B. Abubakirov, K.D. Hahn, and E. Schamiloglu, "Impact of Spent Electrons on BWO Operation," *IEEE Trans. Plasma Sci.,* vol. 37, 560-567 (2009).

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5. C. Watts, M. Gilmore, and E. Schamiloglu, "Effects of Laser Surface Modification on Secondary Electron Emission of Copper," accepted to appear in *IEEE Trans. Plasma Sci.* (2011).

B. Papers in Conference Proceedings

1. M.I. Fuks and E. Schamiloglu, "Amplification and Frequency-Locking in a TWT using Cyclotron Depression of Positive Feedback," *Proc. 2008 IEEE International Vacuum Electronics Conference* (Monterey, CA, 22-24 April, 2008), p. 123-124.

2. J. Gaudet, E. Schamiloglu, J.O. Rossi, C.J. Buchenauer, and C. Frost, "Nonlinear Transmission Lines for High Power Microwave Applications: A Survey," *Proc. of the 2008 Power Modulator Conference* (Las Vegas, NV, May 2008), p. 131-138.
3. E. Schamiloglu and M.I. Fuks, "The Transparent Cathode: Rejuvenator of Magnetrons and Inspiration for New RF Sources," *Proc. Of the IET Conference on High Power RF Technologies* (London, UK, February 2009), p. O1.2 (CD only).
4. S. Prasad, D. Galbreath, M. Fuks, and E. Schamiloglu, "Influence of Implementing Straps on Pulsed Relativistic Magnetron Operation," *Proc. IVEC 2010* (Monterey, CA, 2010), p. 379-380.

C. Presentations

1. C.J. Leach, C. Watts, and E. Schamiloglu, "Plasma Diagnostics to Study Cathodes Used to Drive Long-Pulse Magnetrons," IEEE International Conference on Plasma Science (San Diego, CA, May 31-June 5, 2009).
2. E. Schamiloglu, "Advances in Pulsed Power for Beams Applications," **(Invited)** 10th International Workshop on Plasma Based Ion Implantation and Deposition (Sao Jose Dos Campos, SP, Brazil, September 7-11, 2009).
3. C.J. Leach, J. Osinski, E. Schamiloglu, and C. Watts, "Spectral Diagnostics for the HelCat Helicon/Cathode Linear Plasma Device," Bull. Am. Phys. Soc. vol. 54, No. 15 (2009), Abstract: GP8.00110.

INTERACTIONS

We tested secondary electron emission material for Todd Treado, CPI (Beverly, MA) and Lawrence Ives (Calabazas Creek). We are in discussions with Greg Schaefer (L3 Williamsport, PA) on commercializing UNM's transparent cathode.

Professor Schamiloglu was Invited Speaker, DoD AGED Group, Arlington, VA, June 25-26, 2009.

Professor Schamiloglu was Invited Speaker, Northwest Institute of Nuclear Technology, Xi'an, China, July 31, 2009.

Professor Schamiloglu was Invited Speaker, Jiaotong University, Xi'an China, July 31, 2009.

Professor Schamiloglu was Invited Speaker, Air Force Research Laboratory, High Power Microwave Division, May 11, 2010 (hosted by Dr. Don Shiffler).

RECOGNITION

Professor Edl Schamiloglu was selected Outstanding Engineering Educator (IEEE Albuquerque Local Chapter).

NEW DISCOVERIES, INVENTIONS, PATENTS

Patent Issued: M.I. Fuks, E. Schamiloglu and STC.UNM, "Magnetron Having a Transparent Cathode and Related Methods of Generating High Power Microwaves 07696696 Cl. 315-39.51 (April 13, 2010)